Big Bang Nucleosynthesis and the observed abundances of light elements

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1 Introduction

The standard model of the early universe is extraordinarily simple: it just assumes a globally isotropic and uniform universe. In the simplest version there is no structure of any kind on scales larger than individual elementary particles; indeed the contents are determined by "just physics"— global expansion governed by relativity, particle interactions governed by the Standard Model, and distributions governed by statistical mechanics. Since the gravity is itself dominated by the relavistic plasma early on, parameters that become prominent at late times (global curvature, dark matter density) make no difference, so the model has only one parameter: the ratio η of the number of baryons to the number of photons, often expressed in units of $\eta_{10} \equiv \eta/10^{-10}$. Even this parameter has almost no effect on the early evolution of the universe, but it does affect the principal observational relic of the early expansion, the relative abundances of light nuclei. Since the number of photons in the universe is known today from the microwave background temperature (it is $411 \pm 2 cm^{-3}$), η specifies the present day baryon density: $\Omega_b h^2 = 3.65 \times 10^{-3} \eta_{10}$.

The model would be beautiful even if simplicity were its only virtue, but remarkably, as observations improve they verify it with increasing precision as a good description of the real world. The most precise verification of the basic framework now comes from observations of the isotropy and spectrum of the microwave background, which verify the precise uniformity of the universe on large scales the primordial origin of the radiation. Here I discuss the other principal observational relic of the early universe, the cosmic abundances of light nuclei, which probe homogeneity over a much wider range of scales than the microwave background, and which record processes starting with redshifts of the order of 10^{10}. In particular, I discuss observations of abundances as a precise test of the model and a precise test of the parameter η.

Unfortunately the later evolution of the universe is anything but simple. The uniform gas of the Big Bang long ago converted into a complex universe of

stars and gas, which has undergone considerable nuclear evolution. The main problem is to connect what we can actually observe today with the very clean predictions of the simple Big Bang model, measuring abundances in places where we can uncover fairly well-preserved relics of the initial abundances or deduce constraints on them.

2 The Model Predictions

The nuclear and statistical physics of Big Bang nucleosynthesis are thoroughly studied and its predictions and errors are well characterised using numerical integration of reaction networks to predict the abundances for the light elements ([1],[2], [3]). The predictions can be shown graphically in the traditional plot as functions of η (e.g.[4],[5],[6], [7],). Also useful are the following fitting formulas (adapted from from [8]), including 1σ theoretical errors estimated by Monte Carlo techniques. The predicted fraction of total baryon mass in helium-4 is given by

$$Y_P = 0.235 + 0.012 \ln\left(\frac{\eta_{10}}{2}\right)\left(\frac{\eta_{10}}{2}\right)^{-0.2} + 0.011\left[1 - \left(\frac{\eta_{10}}{2}\right)^{-0.2}\right] \pm 0.0006$$

with theoretical error due in about equal parts to uncertainty in the neutron lifetime and in nuclear reaction rates. The abundance by number of deuterium is

$$\left(\frac{D}{H}\right)_P = 15.6 \times 10^{-5\pm0.03}\left(\frac{\eta_{10}}{2}\right)^{-1.6},$$

or

$$\log\left(\frac{D}{H}\right)_P = -3.81 - 1.6\log\left(\frac{\eta_{10}}{2}\right) \pm 0.03$$

with errors dominated by nuclear rates. The abundance of lithium-7 is

$$\left(\frac{{}^7Li}{H}\right)_P = 1.06 \times 10^{-10\pm0.1}\left[\left(\frac{\eta_{10}}{2}\right)^{-2.38} + 0.28\left(\frac{\eta_{10}}{2}\right)^{+2.38}\right],$$

with theoretical error again due to reaction rate uncertainties. The Big Bang produces negligible amounts of anything heavier, and we omit helium-3 from this discussion because its primordial abundance is not measurable.

It is a considerable challenge to measure the actual primordial abundances to a comparable level of precision, both because of uncertainties in measuring present-day abundances and because of uncertainties in modeling the nuclear evolution since the Big Bang. For each of these nuclei however there is a favorite place to look.

3 Helium in extragalactic HII regions

Nuclear evolution after the Big Bang always increases the abundance of helium, usually but not always accompanied by production of heavy elements. At present the primordial abundance of helium-4 is best estimated in hot, low-metal HII regions in low redshift galaxies. The plasma is hot and largely photoionized by hard radiation from young stars. Abundances are estimated from the strengths of the emission lines of hydrogen and helium. Since both are recombining from the same electron distribution, this gives a fairly direct abundance estimate from the relative recombination and transition rates, with only small corrections due to small differential variations with temperature, line radiation transfer, and collisional excitation. In the best studied cases Y is measured with an accuracy of a few percent; for example, in IZw18, Skillman and Kennicutt[10] find $Y = 0.231 \pm 0.006$. Several dozen such regions have been measured with useful accuracy. Broadly speaking, they reveal the unmistakable signature of the Big Bang: a universal minimum abundance of helium, with $Y_P \approx 0.23$.

The sample is large enough to attempt a more precise estimate of Y_P from the set of estimated Y's in various nebulae. A widely adopted technique is to measure the abundance of another element– such as O or N– in several regions, then extrapolate to zero metallicity to estimate the primordial value. This also gives some information about the enrichment history of the gas. A linear relation is not however necessarily expected (especially in such small regions), so one should entertain the possibility that the enrichment is stochastic in character. In this case one should simply take the lowest values, or some set of lowest, best measured values, taking care to avoid a statistical bias in the estimate of Y_P. The final estimate of Y_P turns out to be remarkably insensitive to which assumptions are made or which subsamples are used. Recent independent analyses yield: $Y_p = 0.228 \pm 0.005 \pm 0.005$ ([9]), $Y_p = 0.231 \pm 0.006$ ([10],[11]), $Y_p = 0.232 \pm 0.003 \pm 0.005$ ([12]), $Y_P = 0.230 \pm 0.006 \pm 0.004$ ([13]), and $Y_p = 0.234 \pm 0.005$ ([14]). The fits are dominated by a small number of galaxies (less than 10) which are well measured and show low values of Y. A significantly higher value of $Y_p = 0.243 \pm 0.003$ is derived by Izotov et al ([15], [16]), largely because of a different sample which excludes many of these galaxies.

The systematic error of the order of 0.005 in all of these is mainly due to uncertainties in modeling the HII regions, for example, the amount of neutral helium and the collisional excitation of HI, which tend to cause underestimates of Y, and temperature fluctuations, which tend to cause overestimates. The range of estimates reflects these uncertainties. It will be hard to reduce these errors significantly, but they are well controlled at the 0.005 level. (In particular the uncertainty due to calculated emissivities of helium lines have largely disappeared.)

From the formulas above, an error in Y_P propagates to an error in η via

$$(\delta\eta/\eta) \approx 83\delta Y_P$$

so η is poorly constrained by Y_P, to no better than a factor of two. On the other hand, the helium observations are a powerful confirmation of the Big Bang picture since the prediction is so insensitive to the model parameter. The helium observations are for example clearly consistent with the number of baryons actually observed, which correspond to about $\eta_{10} \approx 2$ (see below).

4 Deuterium in Quasar Absorbers

The nuclear evolution of deuterium is the opposite of helium. It is only made in the Big Bang, and stellar processing always decreases its mean abundance[17]. Except for local enhancements in molecular forms (due to fractionation), the highest reliable abundance gives a lower limit on the primordial value and an upper limit on η. It is quite sensitive to η which makes it the best tool for a precise measurement.

The most promising technique is to estimate the deuterium abundance from quasar absorption lines. They provide a census of material in a wide range of environments over a huge volume of space, in particular including high redshift material which is relatively unprocessed. They also provide in principle a precise estimate of abundance free of many complex astrophysical effects, since the column densities of two species (DI and HI) are related in a simple way to the absolute abundance in the gas (charge exchange reactions for example guarantee that the ionization is nearly identical for the two species), and both column densities in some situations can be accurately estimated from optically thin or damped absorption in Lyman series lines.

In practice the situation is not yet quite so clean. The holy grail in the field is an absorption system with very simple velocity structure (a single isolated cold cloud is best, with a temperature low enough to make the D identification secure), with a flow field and temperature highly constrained by metal lines (but still with low metal abundance, so that D is not destroyed significantly), with high S/N, high resolution data including well resolved, optically thin Lyman series lines and extending well beyond the Lyman limit. No system yet combines all of these attributes, although some come close.

Current results are listed in the accompanying table. Note that the errors quoted are not total errors, but are just the errors from column density parameters in a model fit. They do indicate the precision the technique is realistically capable of, and the total error could be as small as this in a favorable situation.

The best absorber yet found for this purpose is the $z = 3.32$ system in Q0014, where accurate columns can be measured for both the deuterium (from Lyman α) and the hydrogen (from high order Lyman series lines). The formal error is only about 25% in this measurement. There is a nonnegligible probability that the Dα line is not a deuterium feature at all but a hydrogen line at just the velocity where it masquerades as deuterium; such contamination is rare enough that it does not significantly affect either the value or the error,

although it introduces a small upward bias and changes the confidence intervals considerably.

In this and another absorber in the same quasar, we have found evidence ([20],[21])that the deuterium lines are narrow, as expected for a deuterium feature, but unusually narrow for hydrogen. This supports the interpretation of the feature as deuterium since it reduces the probability of an incorrect identification to less than 10^{-3}. There is still the possibility that HI systems of high column tend to be associated with cold, low column HI companion clouds which mimic deuterium and increase the probability of a spurious identification; this possibility we are checking with hydrodynamical cosmological simulations and control samples.

Published and Reported D/H from Quasar Lyman Series Absorption

log D/H	Quasar	z	Comments	Reference
-3.66 ± 0.06	0014+813	3.32	Lyα-Ly 17	[18]
-3.6 ± 0.3				[19]
-3.72 ± 0.1			narrow Dα, Lyα-Lyμ	[20]
-3.73 ± 0.28	0014+813	2.8	narrow Dα, Lyα, metals	[21]
-3.9 ± 0.4	0420-388	3.086	Dα-Dγ, metals	[22]
-3.7 ± 0.1			OI/DI = const. assumed	
> -4.7			conservative	
≤ -3.82	1202-0725	4.672	Dα, metals, high O/H	[23]
-4.64 ± 0.06	1937-1009	3.572	Dα, Lyα-Ly 17, metals	[24]
-4.2 to -4.0	1937-1009	3.572	fit to Tytler et al's model	[25]
-3.95 ± 0.54	0636+680	2.89	Dα, Lyα only	[26]
-4.60 ± 0.08 ± 0.06	1009+2956	2.504	Dα, Ly$\alpha\beta\gamma$, metals	[27]

The pattern emerging from most of these data is that of a ceiling at around $\log(D/H) \approx -3.7$ or $(D/H) \approx 2\times10^{-4}$; no measurements are found significantly above this value, while several accurate estimates lie close to it. This is of course the pattern expected in the model where this is about the primordial value, which is subsequently reduced in patches by stellar processing.

Two of the measurements lie well below the others, leading to a dichotomous situation reminiscent of the former situation with the Hubble constant. This dichotomy can however probably be resolved soon, as either genuine or due to observational artifacts.

If the differences turn out to be genuine, the most likely explanation will be that the low values are caused by patchy D destruction. On the scale of the absorption clouds D destruction does not necessarily correlate in microscopic detail with local metal abundances, since the two effects are dominated by stars of different masses, and the clouds may be small enough (especially for low ionization parameter) not to represent a fair sample of a stellar IMF. For example, in a star formation region of less than about a thousand solar masses, the expected number of massive stars is small enough even with a standard IMF to occasionally have no supernovae at all, so the ejecta are both metal poor and deuterium poor. A few rare low values of D/H may therefore be consistent with a high $(D/H)_P$ and low metals.

For example, in the 1937-1009 absorber fit by Tytler et al [24], there are two components with very different metallicities. If one were to add a third component of dense gas with low ionization parameter and high HI column, with no detected metals (hiding them in low ionization states), in which the deuterium had been destroyed, the D abundance of the other two fitted components could be quite high. If the ionization parameter is low enough, the neutral fraction of the extra component could be high, allowing the extra cloud to be physically small so that the D destruction is plausible, due say to a confluence of stellar winds or a thermally unstable wind shock.

With small numbers of systems we must also admit the possibility of errors interpreting the observations, such as the possibility that the high D/H values are erroneous due to H contamination. A high S/N UV spectrum of the Lyman series of the 0014 absorbers could disprove this possibility, since the narrow D feature (with little turbulent broadening) predicts in detail the shape of the high order H lines. On the other hand , the low D/H values so far are both found in systems where the HI column is difficult to measure accurately because of its high column density and highly saturated lines. Wampler has argued recently that the line spectra of D, H and several ion species described by Tytler et al's model in Q1937-1009 can be fit with three velocity components, yielding an excellent fit with an H column three times lower and D/H three times higher than the two component model. He conjectures that if the data were fit instead of the model, an additional factor of two would be allowed (depending primarily of the true level of flux allowed in the troughs of the high order Lyman series lines), bringing it up to the level of the high estimates, $D/H \approx 10^{-4}$. This can only be true however if Tytler et al have significantly underestimated the flux in the high order lines and the Lyman limit, a possibility that will be tested soon with new low resolution spectrophotometric data.

It is not difficult at present to reconcile the Q1009+2956 data [27] with a high abundance, since the Keck data in that system does not yet extend to the

blue far enough to separate unsaturated components at high resolution; the only good measure of total HI column is from the Lyman limit, but this does not provide a precise fix on where the HI is in redshift (ie, how much of it belongs to the deuterium). Here again, the issue can be resolved with new data— a high resolution UV spectrum.

There is a methodological question of how reliable the whole technique of Voigt profile fitting is for measuring abundances in QSO absorbers. The feeling has been that it probably works well if there are enough independent constraints, such as metal lines and multiple Lyman series lines, and if a good fit is obtained with a fairly simple model. We now have the opportunity to test this leap of faith quantitatively since we have realistic hydrodynamical simulations of the clouds where the "ground truth" is known; these will let us calibrate the accuracy of the profile fitting procedure in naturally occurring clouds, and perhaps to identify those situations where measurements are most reliable, including the use of metal lines to guide the modeling of flows. Certainly with a large enough sample of clouds to deal with interlopers, this is not an insuperable problem, as long as the gas is hot enough that the thermal part of the line broadening is not much less than the spectral resolution (which is true for photoionized D and H under protogalactic conditions seen in HIRES spectra): in this situation the atomic column of optically thin absorption is measured directly and reliably from the optical depth.

It is important to enlarge the sample, both by enlarging the search for a "holy grail" system to other sightlines, and by lowering our standards and extracting information from systems which are harder to interpret. For example, not listed in the table are the recent estimates by Martin Rugers and myself of D/H in seven other systems of the Q0014 and Q0636 lines of sight. They all have large errors (most of them are based on fitting of single line profiles) and each individually carries little weight; nevertheless it is significant that no absorber was found which required a low abundance, the distribution gives a formal estimate of the mean consistent with the best measured systems, and the distribution of Doppler parameters is consistent with the deuterium identification.

5 Deuterium and Helium-3 in the Galaxy

In the Galaxy today, the interstellar $D/H = 1.5 \pm 0.2 \times 10^{-5}$ ([28], [29], [30]) or $1.3 \pm 0.4 \times 10^{-5}$[31]. Although this is a lower limit to the primordial abundance, we do not know the history of the Galaxy well enough to reconstruct the primordial abundance from Galactic observations. If the primordial value were indeed ten times bigger, 90% of the deuterium must have been destroyed by now, or equivalently, only 10% of the gas can be unprocessed. This happens in some chemical evolution models which agree with the other constraints[32]. More than 90% of the disc mass is now locked up in stars and remnants. In successful models, massive, metal-producing stars and supernovae power early

winds which eject much of the enriched gas; the ISM is then replenished by gas quiescently ejected from the envelopes of low mass stars, which has been depleted in deuterium.

Some estimates of $(D/H)_P$ are based on measurements in the solar system—not of D, but of ^3He, which is what D is turned into. This is combined with stellar and Galactic evolution models to derive a limit on $(D/H)_P$, based on the idea that most stars do not destroy ^3He, and that therefore $(D/H)_P$ cannot be too large without producing too much $(D +^3 He)/H$ ([33], [34], [35], [36]). However, we reject this argument as not reliable for at least two reasons: (1) Observations of carbon, nitrogen and oxygen isotope anomalies in giant branch stars, and models of giant branch mixing ("cool bottom processing") inspired by them, have cast doubt on the notion that low mass stars cannot destroy ^3He; processes that can change the isotopes also destroy ^3He by large factors ([37], [38], [39], [40], [41], [42]). (2) Observations of interstellar ^3He in hyperfine-structure emission seem to show that stars can either make or destroy ^3He, and indeed the radial trend in the Galaxy resembles net destruction more than net production[43]. A handful of planetary nebulae[45] show very high $^3He/H$ (much too high to be typical [44]), while HII regions show a large spread of values, including some very low ones which are evidence of destruction[43].

Both of these developments argue for caution in using ^3He for anything other than a probe of Galactic chemical evolution. A growing consensus of opinion favors abandoning helium-3 as a cosmological probe altogether until its Galactic chemical evolution is better understood. Not only is the present abundance difficult to measure outside the solar system, the primordial $D +^3 He$ value is impossible to deduce since the abundance has been altered significantly by an unknown amount and unknown sign.

Recently, solar system measurement of local interstellar "pick-up ions" (by the Ulysses spacecraft [46]) indicate that the abundance today is $^3He/H = 2.1^{+0.9}_{-0.8} \times 10^{-5}$. The sum of this and interstellar deuterium ($D/H = 1.5 \pm 0.2 \times 10^{-5}$) is $3.7 \pm 0.9 \times 10^{-5}$. For the presolar nebula, the guesses from meteorite data are $1.5 \pm 0.2 \pm 0.3 \times 10^{-5}$, $2.7 \pm 0.5 \pm 1 \times 10^{-5}$ and $4.2 \pm 0.7 \pm 1 \times 10^{-5}$, respectively. These numbers are consistent with a steady conversion of D into ^3He, with little other ^3He production; they are also consistent with a destruction of $D +^3 He$ by a factor of two over the last 4.5 Gy. These are interesting and important constraints on Galactic chemical evolution, but do not contain primordial information.

6 Lithium in Old Stars

The primordial lithium abundance estimated from samples of metal-poor halo stars[47] is according to several estimates $\log(Li/H) = -9.80 \pm 0.16$ ([4], [5]), $\log(Li/H) = -9.78 \pm 0.20$ ([48]), log (li/H) $= -9.79$ to -9.76[49]. Substantial uncertainties enter which make lithium a less precise cosmological tool than

either deuterium or helium. The SBBN predictions themselves are uncertain because of uncertain reaction rates. The absolute abundance is uncertain due to modeling of stellar atmospheres (which are more reliable for differential measurements); and extracting primordial abundances from the stellar abundance is perilous since the amount of depletion is still controversial. Abundances of lithium in stellar atmospheres are influenced significantly by settling and mixing, and by steady mass loss and winds. Indeed all three of these processes are thought to be significant in order to get even approximately a plateau independent of temperature as observed. Models which match the plateau predict typical depletion of factors of two. Fields et al. [50] argue that these uncertainties represent additional errors of about a factor of two, $\log(Li/H) \approx -9.8 \pm 0.3$. Even so, it does appear that a primordial abundance exists in the range predicted by SBBN for the best estimates from the other elements.

7 Crisis or Concordance?

The variety of data encourages a wide range of attitudes in comparing with the Big Bang predictions.

The case for a "crisis" in Big Bang nucleosynthesis[51] is based on an upper bound on D/H, leading to a lower bound on η which conflicts with Y_P. As explained above, this bound is not credible. There is no Galactic conflict with a high deuterium abundance, since chemical evolution can destroy D by a factor of 10 or more and match metallicity vs age and other constraints, and the evolution of ^3He is simply unknown.

But how good is the concordance, and how well constrained is η? A sensible and conservative view ([52],[53]) is that the current spread of published results actually reflects ignorance, or "systematic errors". In this case, one can say only that all three elements are broadly consistent with η over most of the range 10^{-9} to 10^{-10}. In spite of the concordance (granted, over a very wide range in relative abundance), this is a somewhat hollow victory for SBBN.

Our goal however is more ambitious; we want a really precise test of the model and a precise measurement of η. If we put some faith in our current best guesses, we can already take the value from the high D/H quasar absorbers, and assign its errors to the primordial abundance: $(D/H)_p = 1.9 \pm 0.5 \times 10^{-4}$. This lets us estimate with some precision, $\eta = 1.7 \pm 0.3 \times 10^{-10}$. Then we make a prediction for helium, $Y_p = 0.233 \pm 0.003$ which is in astonishingly good agreement with the best direct estimates (assuming three light neutrino species as we expect), and a similarly successful prediction for lithium, $\log(Li/H) = -9.75 \pm 0.2$ (see e.g. [54], [50]). It could be that we are already establishing concordance at a new level of precision. If so, we know the mean baryon number density of the universe to $\pm 20\%$ accuracy.

Although it is premature to claim this precision just yet, many of the uncertainties in the current situation will soon be settled by specific observations.

For example, an ultraviolet Keck spectrum of Q1009+2956 would resolve many ambiguities in the determination of low D/H in the $z = 2.504$ absorber. Better signal-to-noise at the blue end of the Q0014 spectrum would help establish the Lyman series fit better and rule out the interloper loophole there. Correlation of D/H with metals deserves close attention as a potentially powerful constraint on chemical evolution models, especially in the low redshift systems now accessible with HST. It would be fascinating to measure D/H in a damped absorber; this would be a different type of environment from those already measured, closer to the conditions in the early Galaxy, and offers the possibility of a very reliable measurement [55].

The helium measurements as well as the high deuterium measurements seem to be pointing us in the direction of low baryon density, $\eta_{10} \approx 2$, $\Omega_b \approx 0.015$ for $h = 0.7$. It was clear at Princeton that such a low value is not particularly popular with model builders. One reason is that it tends to imply a low density universe. For example, we can use the cluster baryon fraction (using Steigman's equation 3) to infer that the density of dark matter is only $\Omega \approx 0.12$; even allowing for systematic errors with cluster masses or baryon segregation, this clearly implies an open universe or one dominated by a cosmological constant.

We can also compare this density with an inventory of known baryons in the universe. The accompanying table summarizes estimates of the integrated density of known forms of baryons, by integrating various mass functions based on systematic surveys (e.g., [56], [57],[58]). Because the dependence on h varies, they are shown just for $h = 0.7$. The errors in the estimates are not well calibrated but could easily be a factor of two for most components. The bottom line is certainly consistent with a low baryon density, and indeed in this case there is not a large reservoir of dark or unaccounted baryons. If the baryon density is much higher, the extra baryons must be hidden somewhere, which is increasingly difficult as constraints improve on the density of compact objects ([59], [60]) and intergalactic gas.

Baryon Densities for $h = 0.7$

Form	Ω_i
Stars in spheroids	0.0032
Stars in disks	0.0017
Stars in irregulars	0.0002
Neutral atomic gas (HI, HeI)	0.00033
Molecular gas	0.0002
Plasma in clusters	0.0026
Plasma in groups	0.0031
Cool intergalactic gas clouds	0.002
sum	0.013

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